A Comment on Spin Nomenclature for Semiconductors and Magnetic Metals

B.T. Jonker[a] and A.T. Hanbicki
Naval Research Laboratory
Washington, D.C. 20375-5343

D.T. Pierce and M.D. Stiles
National Institute of Standards and Technology
Gaithersburg, MD 20899-8412

a) Electronic mail: Jonker@nrl.navy.mil

A recent Letter[1] and subsequent Comments[2,3] describing electrical spin injection from a ferromagnetic metal into a semiconductor highlights the fact that there is some confusion relating the sign of the polarization of the spin density in a semiconductor to the direction of magnetization in a ferromagnet. Confusion arises from differences in usage conventions in different research communities and because of imprecise terminology. In particular, the term "polarization" means definite things to many people, and frequently those definite meanings differ. The nomenclature in the semiconductor community is based on the orientation of the carrier *spin*, an experimental observable which is accessible using standard optical spectroscopic methods, while in the magnetic metals community the nomenclature is based on the orientation of the *moment*, the basic experimental observable in a wide variety of magnetometry techniques.

Generally, polarization is the degree to which one spin state is occupied relative to the opposite spin. The connection between a measured polarization and materials properties depends on the particular measurement.[4,5] For instance polarization can be defined for densities $P = (n_\uparrow - n_\downarrow)/(n_\uparrow + n_\downarrow)$, or currents $P = (j_\uparrow - j_\downarrow)/(j_\uparrow + j_\downarrow)$. These two quantities are not directly related and need not have the same sign or even be collinear when the appropriate vector quantities are considered. Relating them requires a transport calculation; e.g. for diffusive transport in a non-magnetic material, $(j_\uparrow - j_\downarrow) = -D\nabla(n_\uparrow - n_\downarrow)$, where D is the diffusion constant. No single value of polarization describes the spin-dependent properties for a particular material. Further, in different systems, the sign of the polarization is determined by different conventions. In this note, we focus on these conventions. Although the material presented is basic and available in various references, given the subtleties and potential for sign errors, we hope that bringing the information together in one place and suggesting a standard convention will be useful.

To focus this discussion we will use as an example our experiment described in a recent Letter[1]. In this experiment we utilized the optical emission from an AlGaAs/GaAs-based quantum well light emitting diode (QW LED)[6] to measure the spin polarization of electrons in the QW which were electrically injected from a reverse biased Fe Schottky contact. The experiment was done in the Faraday geometry, shown in Fig. 1, where the magnetic field direction is parallel to the light propagation. In this case, the Fe magnetization and the outgoing light were in the direction normal to the surface of the ferromagnet, which we take as the z axis. Note that other experiments measure the emitted light in the reverse direction, i.e. out the back side of the wafer, and we will point out how that situation differs. Because angular momentum is conserved in this experiment, it is useful to discuss the experiment in terms of the angular momentum along the z-axis of the light, of the spins in the ferromagnet, and of the spins in the semiconductor. We consider each now in turn.

First, for the case of light, the circular polarization of light emitted from a QW LED is defined independently of a chosen quantization direction as

$$P_{\text{circ}} = \frac{I(\sigma^+) - I(\sigma^-)}{I(\sigma^+) + I(\sigma^-)}$$

where $I(\sigma^+)$ is the intensity of positive helicity (σ^+) light. Note that different conventions call σ^+ light left (optics convention) or right circularly polarized (angular momentum convention). Positive (negative) helicity light always has angular momentum parallel (antiparallel) to the propagation direction of the light. For outgoing light along the z-axis (Fig. 1), $\sigma^+(\sigma^-)$ light has angular momentum +1 (-1) (Fig. 2a).

In the ferromagnet, the magnetization, or magnetic moment density, is a well defined quantity and gives a suitable reference direction in a ferromagnet. The magnetic moment of an electron is $\vec{\mu} = -g\mu_B \vec{s}/\hbar$, where $|\vec{s}| = \hbar/2$ and we take g to be positive for a free electron, as is customary in solid state physics. The minus sign is written explicitly to show that the electron magnetic moment and electron spin $\vec{s}$ are in opposite directions (Fig. 2a). It is important to note here that in the most recent compilation of fundamental constants,[7] and in some texts in other fields of physics, the minus sign is absorbed in the g factor and the free electron g factor is *negative*. The g factors for electrons in the ferromagnetic metals Fe, Co and Ni, where there is little orbital contribution to the magnetic moment, are 2.10, 2.18, and 2.21, respectively. This means the electron spin and magnetic moment for these materials are *antiparallel.*

In ferromagnets one spin has more occupied states (majority) than the other (minority) because of an exchange interaction. The polarization P_{FM} in a ferromagnet is usually defined as the density of majority spins (or moments) minus the density of minority spins divided by the total number of electrons. If the quantization axis is chosen to be the magnetization direction, the ferromagnetic polarization is equal to the polarization defined in terms of moments

$$P_m = \frac{n_{m\uparrow} - n_{m\downarrow}}{n_{m\uparrow} + n_{m\downarrow}}.$$

Here $n_{m\uparrow}(n_{m\downarrow})$ refer to the number of electrons whose **magnetic moments** are parallel (antiparallel) to the magnetization. In ferromagnets, up and down usually refer to majority spin and minority spin respectively, independent of the quantization axis.

In semiconductors, on the other hand, polarization is usually defined in terms of the spin direction

$$P_s = \frac{n_{s\uparrow} - n_{s\downarrow}}{n_{s\uparrow} + n_{s\downarrow}},$$

where $n_{s\uparrow}(n_{s\downarrow})$ refer to the number of electrons whose **spins** are parallel (antiparallel) to z. Again, given the potential for sign errors, it is important to make explicit whether the polarization is defined in terms of moments or spins, and to note the sign of the g factor. In contrast to the usage in describing ferromagnets, in semiconductors, up and down usually refer to the direction of the electron spin relative to a chosen quantization axis.

In the semiconductor, the electron spin states are designated by their m_j quantum number relative to the quantization axis, typically taken to be the z axis. We can take the z axis along the light propagation direction or the magnetization. For the specific case considered here, these are the same. The electron states at the conduction band minimum and valence band maximum are shown in Figure 2c. In semiconductors, owing to large spin-orbit contributions and small effective masses, g factors may vary significantly and even change sign. For an applied magnetic field along z, an electron with quantum number m_j = -1/2 (spin opposite to the applied field) has lower energy and is therefore preferentially populated in materials with a positive g-factor such as ZnMnSe. In contrast, for conduction band states in GaAs g=-0.44, so the m_j = +1/2 state has lower energy in an applied magnetic field; in this case, the conduction electron spin and magnetic moment are in the same direction.

The measurement of reference 1 relates the polarization of light to the polarization of the semiconductor and the ferromagnet. Sign errors can be avoided by using angular momentum conservation in a chosen reference frame. Thus, it is useful to convert the polarizations of the ferromagnet and the semiconductor to angular momenta with respect to the light propagation direction, again see Fig. 2.

The two transitions relevant to the present geometry are shown in the diagram of Fig. 2c. The solid line shows the -1/2 to -3/2 transition with $\Delta m_j = -1$. To conserve angular momentum the photon generated must take away angular momentum +1 and hence is σ^+ light for the geometry considered here. The converse is true for the transition shown by the dashed line. The spin density in the conduction band at the time of the optical transitions is determined from the measurement of P_{circ}

$$P_{\text{circ}} = \frac{I(\sigma^+) - I(\sigma^-)}{I(\sigma^+) + I(\sigma^-)} = \frac{n_{-1/2} - n_{+1/2}}{n_{-1/2} + n_{+1/2}} = -P_s$$

where $n_{+1/2}(n_{-1/2})$ is the density of spins parallel (antiparallel) to the z axis and P_z is the usual definition of spin polarization along the z axis. In the case of reference 1, electrical spin injection of electrons from a reverse-biased Fe Schottky tunnel contact into a GaAs QW results in preferential population of the m_j = -1/2 ($n_{s\downarrow}$) QW state for Fe magnetization along z, as demonstrated by the circular polarization of the accompanying luminescence. These carriers correspond to majority spin carriers ($n_{m\uparrow}$) in the Fe contact. Note that the measured density polarization is not directly related to the polarization of the current crossing the barrier, which must be inferred from the measured polarization of the density and a transport calculation.

If the circular polarization of the light is measured out the back side of the structure a similar analysis obviously applies. If the experimental geometry is the same as in Fig. 1 except the light is collected in the reverse direction, one would expect to find light of the opposite helicity as shown in Fig. 2. To keep track of signs and to enable comparison of results of different experiments, the quantization axis chosen for the semiconductor spins, and how other quantities like magnetic field are referenced to it, should be explicitly stated. If the quantization direction is chosen to be the light propagation direction, the transitions in the semiconductor have the same form as they do for light coming out the front.

A final comment needs to be made about the modifiers majority and minority, and up and down. These labels frequently mean different things when describing electrons in ferromagnets and in semiconductors. In ferromagnets, majority and minority refer to the direction of the moment of each electron, and in semiconductors to the type of carrier, electron or hole. In papers that overlap both fields, we think it is more useful to speak of minority and majority spins and majority and minority carriers rather than (ambiguously defined) majority and minority electrons.

In summary, the nomenclature in the semiconductor community is based on the orientation of the carrier *spin*, an experimental observable which is accessible using standard optical spectroscopic methods, while in the magnetic metals community the nomenclature is based on the orientation of the *moment*, the basic experimental observable in a wide variety of magnetometry techniques. The respective terminology which is commonly employed can result in some confusion as these fields interact in the semiconductor spintronics arena. Consequently, care must be taken to insure accurate communication of experimental and theoretical results. Confusion can be avoided by describing everything in terms of angular momenta in a common reference frame.

[7] P.J. Mohr and B.N. Taylor, Physics Today, BG6, August 2002

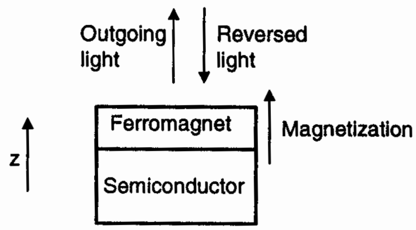

Figure 1. Geometry and directions.

	Moment along z	Angular momentum along z	Helicity
a) Light			
Outgoing		+1	σ_+
		-1	σ_-
Reversed		+1	σ_-
		-1	σ_+
b) Ferromagnet			
Majority	$g\mu_B/2$	-1/2	
Minority	$-g\mu_B/2$	1/2	

c) Semiconductor

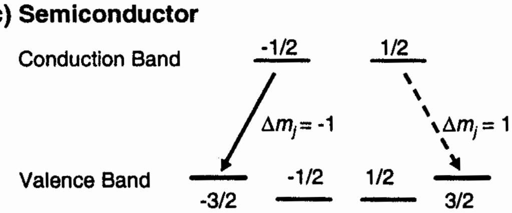

Figure 2. Angular momenta for light emission from GaAs. The third column shows the angular momenta (in units of $\hbar$) of light and electrons in the ferromagnet and semiconductor. The second column gives the moment of the same electrons in the ferromagnet and the final column gives the helicity of the light. At the bottom, the third column is expanded to give the angular momentum of states in the semiconductor at the conduction band minimum and valence band maximum.

References

[1] A.T. Hanbicki et al, Appl. Phys. Lett. 80, 1240 (2002)

[2] R. Jansen, Appl. Phys. Lett. 81, 2130 (2002).

[3] A.T. Hanbicki and B.T. Jonker, Appl. Phys. Lett. 81, 2131 (2002).

[4] R.J. Soulen Jr., J.M. Byers, M.S. Osofsky, B. Nadgorny, T. Ambrose, S.F. Cheng, P.R. Broussard, C.T. Tanaka, J. Novak, J.S. Moodera, A. Barry, J.M.D. Coey, Science, 282, 85 (1998).

[5] I.I. Mazin, Phys. Rev. Lett. 83, 1427 (1999).

[6] B.T. Jonker et al, Phys. Rev. B 62, 8180 (2000).

[7] P.J. Mohr and B.N. Taylor, Physics Today, BG6, August 2002.